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A Framework for Extended Reality System Development in Manufacturing

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ABSTRACT This paper presents a framework for developing extended reality (XR) systems within manufacturing context. The aim of this study is to develop a systematic framework to improve the usability and user acceptance of future XR systems. So that manufacturing industry can move from the ‘‘wow effect’’ of XR demonstrators into the stage whereas XR systems can be successfully integrated and improve the conventional work routines. It is essential to ensure the usability and user acceptance of XR systems for the wider adoption in manufacturing. The proposed framework was developed through six case studies that covered different XR system developments for different application areas of manufacturing. The framework consists of five iterative phases: (1) requirements analysis, (2) solution selection, (3) data preparation, (4) system implementation and (5) system evaluation. It is validated through one empirical case and seven identified previous studies, which partly aligned with the proposed framework. The proposed framework provides a clear guideline on the steps needed to integrate XR in manufacturing and it extends the XR usage with increased usability and user acceptance. Furthermore, it strengthens the importance of user-centered approach for XR system development in manufacturing.

INDEX TERMS Extended reality, virtual reality, mixed reality, augmented reality, virtual manufacturing.

I. INTRODUCTION

Over the last 20 years, extended reality (XR) systems are gaining increasing attention in both academia and industry [1], [2], thanks to the latest technology advancement which makes XR ever matured. It includes the different approaches of the entire spectrum from complete real to complete virtual under the reality-virtuality continuum [3]. Many studies have shown that XR technologies can be integrated to improve various manufacturing related activities covering all phases from design to operation and service [4]–[9]. The successful integration of XR systems is essential in the digital transformation of manufacturing and it will contribute to the realization of the Industry 4.0 vision. Despite the reported studies have demonstrated great potentials of XR applications in manufacturing, there are few XR systems are being used by engineers in their daily work routines [10], [11]. It shows that XR systems integration in manufacturing is difficult and challenging [12]. In the manufacturing world, it is already so complex with existing systems, different stakeholders and rigid constraints for quality, safety and reliability. The introduction of XR systems would bring in not only the promised benefits, but also completely new ways of human-computer interaction for both system developers and end users. In the year of 2020, the pandemic of COVID-19 have resulted in more distance meetings and social distancing. This will increase the use of XR in many areas such as health care [13], tourism [14] and education; it might also fasten the evolution of technology within manufacturing [15] as well. However, there is a lack of established guidelines to support such an integration process of XR systems in the manufacturing context.

This has resulted the fact that most attempts stopped at the ‘‘wow effect’’ stage and failed to provide the promised benefits. In order to facilitate such integration with the intended wider usage, this study set out with the aim of developing a systematic framework to support future XR systems development in manufacturing that will. A framework is therefore derived based on six real-world case studies and validated through an empirical case and seven previous studies, which partly aligned with the proposed framework.

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II. FRAME OF REFERENCE

A. EXTENDED REALITY CLASSIFICATION

The concept of enhancing human perception through computer-mediated reality dates back to 1960s [16]. Over the

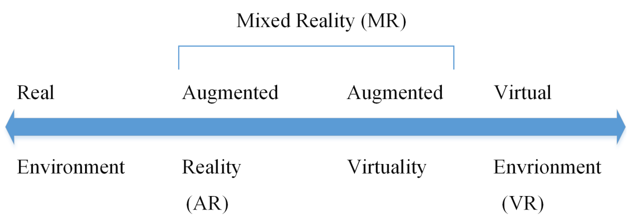


FIGURE 1. Relation between the extended technologies and the environment [3].

years, it evolved into different subsets and resulted in different terminologies that can be confusing for many. In this paper, XR is used as the umbrella term to represent all computer-mediated reality technologies that merge the physical and virtual worlds for the enhanced experience.

It is important to distinguish the different types of XR systems so that right decisions can be made for any specific applications in manufacturing [17]. A widely adopted approach is the reality-virtuality continuum whereas real-world environment and virtual environment are on each end [3]. As shown in Fig. 1, with the amount of virtuality increases from the left to the right, comes the augmented reality (AR), mixed reality (MR) and virtual reality (VR).

1) AUGMENTED REALITY

The most widely accepted definition of AR was proposed by Azuma in his 1997 survey paper [18]. According to Azuma AR must have the following three characteristics:

- combines real and virtual
- interactive in real time
- registered in 3D

In AR systems, digital contents such as information and objects are overlaid in the real world. This means that users can still see and interact with the surrounding environment while getting the enhanced experience with digital details such as text description, image and animation illustrations. Either it is through wearable devices e.g. smart glass or handheld devices e.g. smart phone, to provide users with the enhanced experience. The IKEA Place app[1] is a typical example of AR application, which allows customers to visualize the products being overlaid onto the living space through a smart phone.

2) MIXED REALITY

Mixed reality can be defined as applications where 'real world and virtual world objects are presented together within a single display, that is, anywhere between the extrema of the virtuality continuum'[19].

The MR systems take one-step beyond AR because the virtual objects are not only overlaid onto the real world, but users can also interact with them as if they were real objects. To achieve the MR experience, a headset that equips with integrated computer, translucent glass, and sensor is needed. The real world environment is usually mapped in real-time with the integrated sensors, so that virtual objects can interact with the actual environment and by the users. In a sense, MR is a more immersive and interactive type of AR. A famous example of MR headset is the Microsoft HoloLens,[2] which can be found in many reported MR applications.

3) VIRTUAL REALITY

VR can be defined as "*The use of real-time digital computers and other special hardware and software to generate a simulation of an alternate world or environment, which is believable as real or true by the users*." [20].

The VR system sits in the right-end of reality-virtuality continuum, which is made of completely computer-generated content. Users are fully immersed in the virtual environment without the possibilities to see and interact with the real-world environment. The full immersion and high level of presence in VR systems give great flexibility to play what-if scenarios. There are three typical setups for VR systems. The entry one is with a standalone headset that is either through combination of a smart phone with a cardboard or integrated solution to provide the virtual experience. CAVE (Cave Automatic Virtual Environment) is another setup with multiple large projecting screens as walls and floor of a room, where users are fully immersed. The last setup is through the head-mounted display (HMD) that is connected to a standalone computer. This setup has become dominant in recent years as it is becoming ever affordable and retain great VR experience.

B. HARDWARE PARAMETERS FOR EXTENDED REALITY

After clarification of the XR system types, it is also important to have deep understanding of the different hardware parameters, which would affect the overall usability of the systems. Several key parameters were identified from reported studies and summarized in this section.

1) FIELD OF VIEW

In any XR systems, it requires a screen to project the virtual content to the users. The field of view (FOV) parameter of a screen would define the extent of the visible area to a user at any given moment. It directly affects the amount of virtual information that can be rendered. Human eyes have a binocular FOV around 114 degrees horizontally [21] and it is idea for screen used in XR systems to have similar FOV so that users would have seamless experience while all important information can be properly displayed. However, different screens available today have varied FOVs. Normally, AR and VR devices would have a much smaller FOV between 30–60 degrees, which means limited virtual content can be presented at a time. It is proved problematic when large virtual objects need to be rendered. However, as the real-world environment is not excluded from the AR or MR systems, the limited screen view would not affect user's perception if virtual content were adapted to the proper size. VR headsets today have a wider FOV between 90–110 degrees;

[1] https://apps.apple.com/us/app/ikea-place/id1279244498

[2] https://www.microsoft.com/en-us/hololens

some advanced models even claim 200 degrees, which is more than human's nature FOV. Since users are fully immersed with digital content, the FOV becomes more important with regard to the user experience. Headsets with smaller FOVs were proved noticeable and distracting to users with the so-called "tunnel vision effect".

2) FRAME PER SECOND

Another crucial parameter associated with the screen is the frame per second (FPS). It is the frequency at which consecutive frames of image displayed on a screen [21]. The higher FPS means smoother motion of the content. Similar to the FOV, this parameter is more important in VR systems than AR or MR systems. While 30–60 FPS would be enough for AR or MR systems, it is recommended to strive for 90 FPS for VR systems. Because users were immersed with completely computer-generated content, lower FPS would result in motion jitter, which would cause users motion sickness. However, it is worth noting that FPS is not only determined by the hardware, but also the software, so it is also important to fine-tune the virtual scenes in the development to achieve the desirable FPS.

C. SOFTWARE FOR EXTENDED REALITY

The XR systems used in manufacturing are developed using various software. The author categorizes them into two major approaches, which are based on open development platform and extension of established commercial software respectively. Open development platform has the advantage with fully controlled development process that can be tailed on individual needs, but requires the expertise in software engineering. Established commercial software that are already being used in today's manufacturing is also expanding the support for XR features. Thus, existing users can create seamless XR experience without much effort. However, there is limited freedom to explore new features of XR with such software, as it is dependent on the update from the software providers. A selection of the examples from these two approaches will be described in the following section to provide better context for this study.

1) OPEN DEVELOPMENT PLATFORMS

Among the different open platforms that support XR development, Unity3D[3] and Unreal Engine[4] are the two dominant ones. Both started in the gaming industry and have expanded to be used by other industries in recent years. The large and vibrant community in these platforms have provided fast evolving plugins that manufacutring industry can quickly adopt for its customized XR development. While Unity3D has established itself in the manufacturing field through collaboration with leading manufacturers around the world, Unreal Engine is renownd for its relative ease creation of photorealistic visualization.

A keyword search in Scopus[5] shows that the amount of publications that used Unity3D in the development of XR applications surged from only two publications in the year of 2008 to 611 in 2019. The open platforms are playing an increasingly significant role in the XR development.

2) ESTABLISHED COMMERCIAL SOFTWARE

As the XR technology is getting ever matured and gaining increasing attention, existing commercial software that are being used in today's manufacturing are also expanding their support with various XR features.

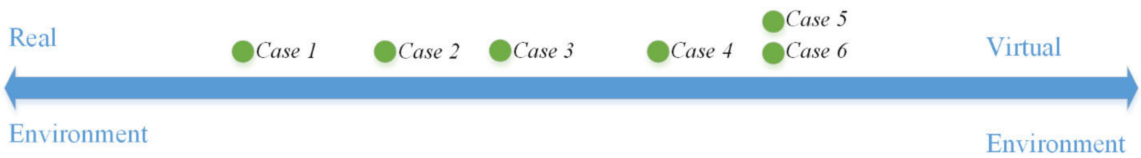
Plant Simulation from Siemens with the extended VR support to visualize and interact with the simulation models have reported to facilitate analysis of the assembly line design [22] and maintenance training for steam turbine [23]. VRED from Autodesk is used to aid the product design in terms of perceived quality thanks to the realistic visualization of product design in VR [24]. The VR feature extended in the latest version of Robot Studio from ABB helped achieve better workplace station of creating robotic system [25]. Vuforia Studio enabled fast AR application development for operator support and training [26], [27]. These are a few examples of the reported XR applications that were developed using established commercial software. While this path lacks the freedom to tailed higher degree of customization, it saves the time and cost to (re-)create common functions and facilitate the XR integration in manufacturing industry.

D. PREVIOUS STUDIES

The manufacturing industry is moving towards an ever-digitalized era and various XR technologies including AR, MR and VR are the key pillars in this digital transformation. The trend is evident with the increasing number of reported studies about XR applications in manufacturing, such as in the area of factory layout planning (FLP), assembly and training [2], [28], [29].

Okulicz developed a VR-based manufacturing and layout planning system which focused on evaluating the ergonomics and accumulated loads for operators [30]. Aurich *et al.* further developed the continuous improvement process (CIP) workshop for FLP by integrating VR technology and proposing a VR-based CIP workshop [7]. They demonstrated that CIP workshops within a virtual manufacturing environment can successfully transfer the results back to the physical environment. Choi *et al.* introduced a rule-based system, which creates a virtual prototype using product, process, plant and resource data in a virtual plant review [31]. They proposed a new virtual plant review procedure. In the same year, an approach to immersive multi-projection visualization of manufacturing processes was reported [32]. This allows scenarios involving dynamic components, plus collaborative VR visualization between geographically distributed users. An AR-based hybrid approach was developed to facilitate onsite factory layout planning and evaluation in real

[3] https://unity.com/
[4] https://www.unrealengine.com/
[5] https://shorturl.at/txFNU



	XR types	Case company	Case area	Phases	Year
Case 1	AR, Meta 2	Snus production	Maintenance training	Disruptive	2018
Case 2	AR, MR, HoloLens, Tablets	Drone factory in Lab	Assembly support	Operational	2019
Case 3	MR, HoloLens	Ventilation production	Order picking in warehouse	Operational	2018
Case 4	VR, HMD	Drone factory in Lab	Assembly training	Training	2019
Case 5	VR, HMD, Leap Motion	Truck production	Design for maintenance	Design	2019
Case 6	VR, HMD, Leap Motion	Car production	Product design review	Design	2019

FIGURE 2. The cases summarized in relation to the reality-virtuality continuum.

time [33]. Thus, users are fed an augmented visualization of the factory with candidate equipment to be laid out and corresponding decision-making support, based on the geometric data, defining the criteria and constraints. VR has also been reported as being used as an interactive solution for loop layout problems. This solution reduced the gap between traditional numerical and analytical simulation results and the real situation by using an enhanced human-machine interface [9].

Many of these studies also have devoted to assist assembly and maintenance work as well as workstation design and simulation. Yao *et al.* proposed the immersive virtual assembly planning and training system (I-VAPTS) for complex pump assembly processes [34]. Peng *et al.* further improved on this via a hybrid method using rule-based reasoning and fuzzy comprehensive judgment to capture the user's operational intent and recognize geometric constraint [35]. Funk *et al.* developed the General Assembly Task Model using task-dependent and task-independent measures, so that uniform experiment design can be achieved when assessing the effectiveness of the XR solutions [36]. The stationary spatial AR systems for spot welding tasking were reported to improve the efficiency [37], [38] and achieve a higher degree of precision and accuracy [39], [40]. Franceschini *et al.* developed and tested an AR system based on imaging processing algorithms to assist the product quality inspection. The preliminary results proved that given properly used, it might lead to remove human errors due to distraction, fatigue and lack of training [41]. Kosch *et al.* used a commercial electroencephalography (EEG) device in an assembly experiment, which demonstrated the cognitive load for assembly operators using projected in-situ system is alleviated compared with conventional paper instruction approach [42]. In 2020, a framework was proposed for unifying simulation and VR for human-robotic collaboration design and planning [43]. The study demonstrated the framework is feasible and reliable in better visualizing the workstation design with the help of VR. With the increasing number of publication in this area, Büttner *et al.* developed a framework that can help identify research opportunities for XR applications in manufacturing, through a web-based visualization that collect and classify the relevant previous studies [44]. Moreover, while these reported studies have shown the advantages of integrating XR technologies in manufacturing, it is still not widely adopted in the real world factory. Masood and Egger pointed out that while companies are striving to learn and adopt AR, the attempts may fail due to lack of understanding critical success factors and key challenges for industry AR integration. Through industry survey and field experiments, they have found that, while technological aspects are important, organizational issues are more relevant for industry and it has not been reflected to the same extent in literature [45], [46].

III. RESEARCH APPROACH

Due to the variety of XR systems and the complex nature of different manufacturing areas, multiple cases have been investigated for the goal of developing a framework that can improve the usability and user acceptance of future XR systems. Accordingly, six cases were selected as they represent the integration of the whole range of XR systems for the four phases of manufacturing activities at different companies, namely design, training, operation and disruptive. They are summarized in Fig. 2 as in relation to the reality-virtuality continuum. It is worth point out that All cases chose the open platform development in Unity3D as the diverse and customized functions of the cases and projection-based AR solution is not included in the scope of the study. Each case focused on supporting one manufacturing activity with an XR system. It is a continuous refining process that early case result helped improving later ones, while the later cases complemented with new activities and solutions. The result from all the cases forms the foundation for the developed framework that facilitates future XR system development with increase usability and user acceptance. The proposed framework was validated through an empirical case and seven external studies.

A. RESEARCH PROCESS

All the six case followed the systematic empirical research approach inspired by Flynn *et al.* [47]. Each case started with context inquiry in the form of field trip, observation or interviews for the problems at the case company, as well as the literature review of the relevant area. Then, potential

XR solutions were discussed and decided together with stakeholders at workshops. Thereafter, the XR system was implemented based on the agreed requirements. The developed XR systems then would be tested by participants representing all the involve stakeholders at the case company. During the user tests, performance measurements such as completion rate and time were recorded for later analysis. Depending on the individual test design in these cases, follow-up questionnaires based on system usability scale (SUS) [48] and self-assessment manikin (SAM) [49], as well as semi-structured interviews were used in between different tasks or after the completion of the entire test. The questionnaire results and the interview data collected through the tests were converged to evaluate the outcomes of the proposed XR solutions for the specific manufacturing problems. The findings in these six case studies were therefore served as the basis for creating the proposed framework for XR development.

IV. FRAMEWORK DEVELOPMENT

The system development life cycle (SDLC) was adopted in the development of the framework for XR system integration in manufacturing context. The SDLC, also known as application development life cycle, which is widely used during the development of IT systems [50]. It describes the multi-phases of activities for system designers and developers to follow to ensure the quality of the system development. Over the years, various models and methodologies have been developed based on the SDLC approach, such as the old fashion waterfall model [51] to the user-centered design (UCD) [52] scrum [53].

In this study, the SDLC phases adopted in the analysis of the cases are listed below:

- Identifying problems
- Analyzing the needs
- Designing the system
- Developing and documenting
- Testing the system
- Implementing and maintenance

The six cases are therefore summarized in the following sections and consolidated based on the chosen SDLC phases for the development of the XR system development framework.

A. CASE 1

1) BACKGROUND

Maintenance of machines and equipment in the production lines has always been an important task for all manufacturing companies. It helps ensuring the expected uptime and throughput in the factories. Previous studies have shown that costs associated with maintenance accounts a large proportion of the total production costs [54]. With the Industry 4.0 initiative, increasing digitalization and automation are found in today manufacturing. While this trend promises more reliable and efficient production, it also on the contrary poses much higher requirement for crucial human intervention to ensure such systems are working as expected [55].

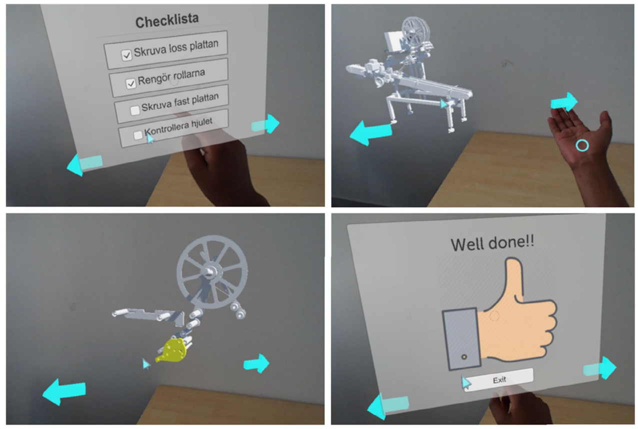


FIGURE 3. Screenshots from the AR maintenance support system.

Contemporary digital technologies are also needed to better support maintenance experts instead of the experience-based or paper instruction-based work approaches [56]. The recent advancement in AR hardware and software show great potential to empower maintenance experts in this matter.

2) RESEARCH PROCESS

An case study was carried out at a snus manufacturing company in Sweden [57]. It aims at exploring and evaluating the effects of wearable AR support system for maintenance instructions. The study is divided into two phases. In phase one, with some background studies of the available AR technologies, an AR system that supports the maintenance tasks of a small toolbox was developed. It was shown in the largest maintenance fair in Sweden and tested by 17 practitioners in the field. Observation and questionnaire were used to collect data to gain better knowledge and contributed to the development in the second phase, where the AR system was upgraded with a real machine maintenance task from the case company. The machine was selected for the need of high maintenance frequency after the field trip to the company as well as discussion with their maintenance engineers. There were 16 representatives from the company tested the new AR support system, while same methods of observation and questionnaire were used to evaluate the effects of the system. Several screenshots are merged in Fig. 3 to show the AR system interface.

3) RESULTS AND CONCLUSION

From the first test, we noticed that users needed longer time than we have expected to get started with the system and had trouble switching focus in between the physical world and the augmented instruction. More importantly, text based instruction were largely neglected. With the upgrade AR system in the second test, measures such as replacing text instruction with appealing object symbols helped make the users better grasp the intended information. The rich content augmented to user's eyes are more vivid than the text or picture-based instruction in papers. Questionnaire results from both tests are overall positive to the tested system and AR technology with more than 80% of participants rated 4 out of 5 for all the statements in the questionnaire.

However, the results can be skewed by the wow factor of the first time use of such an AR system. Design problems related to presenting instruction in an easy to comprehend manner in AR interface are still mostly unresolved. Another big drawback is that the system used a wearable AR glass that needs to be cable-connected with a computer to work, which would greatly limit the usage of such system in the actual factory floor. The questionable choice of the AR hardware is connected with the unclear goal at the beginning on whether the AR support system would be used in training maintenance operators' offsite or guide the maintenance operations onsite.

To conclude, this study has shown AR technology can be used to better support maintenance in manufacturing. However, the lessons learned for furture XR development are firstly, instruction design for AR interface is different from the conventional 2D interface, therefore requires more research attention that involves users early into the system development process. Secondly, before introducing AR system to the manufacturing context, it is important to have both good knowledge of the intended manufacturing activity as well as the available AR technologies, so that the most suitable solutions in terms of hardware and software can be used to achieve the optimal outcome.

B. CASE 2

1) BACKGROUND

Manual assembly has always been an important part of manufacturing and it holds as true even today with increasing automation as manufacturing industry is embracing the fourth revolution [58]. The changes are reduced total amount of manual assembly tasks, but increased complexity and knowledge requirement. This is due to the shifting trend of mass customization which in turn results in low volume but high variants production [59], [60]. Recent studies have shown that the emerging AR technology has great potential to support operators with real-time instructions during the assembly work [8]. However, studies also indicate the user acceptance for AR system is low and there is still no widely used AR system in manufacturing [61]. Part of the reason is the new medium of human-computer interaction in AR is new to end users and developers. Therefore, it is worth investigating the effect of different interaction design approaches on the AR system development and end user experience.

2) RESEARCH PROCESS

This study took the case from an assembly workstation in the drone factory in a Swedish national testbed laboratory [62]. The drone factory were mainly rely on conventional operstor support such as paper instructions and animated visual illustration in monitor. In this study, it focused on three aspects related to the new possibilities associated with AR system. First, it included the different ways of presenting the instruction based on the structural diagram and action diagram [63].

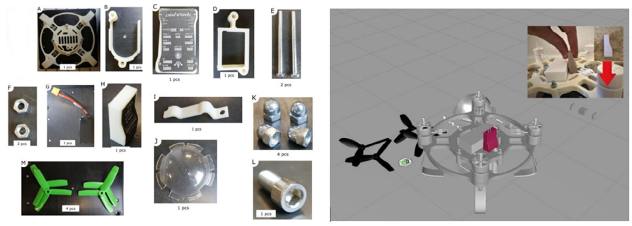


FIGURE 4. The components needed in the assembly (left), the screenshot of the AR instruction (right).

Second, both the hand-held AR using tablet and the wearable AR using Microsoft HoloLens were used in the study. Lastly, two controls of the instruction flow using touchscreen buttons and voice command were also included. Therefore, the AR assembly support system with those features was developed and tested. Twelve participants were randomly assigned to the tablet and HoloLens groups. All performed the assembly task with respective support. The assembly task and AR instruction are shown in Fig. 4. The completion time and quality as well as after test feedback were recorded so that analysis was done to provide insights for future AR system design with regard to those three aspects.

3) RESULTS AND CONCLUSION

It shows that the assembly operations with action diagram-based instructions were completed with less time and high accuracy than the structural diagram-based approach, even though action diagram-based instruction usually will take longer time to play as there are animation involved. The follow-up questionnaire also show users prefer to have animated instructions as demonstrated with the action diagram-based approach. The tablet group performed better on average than the HoloLens group. This is well correlated with user's previous experience with the devices as the touchscreen interaction is already widely used and accepted. Observation also found that users were quite nervous when moving and assembly with the wearable AR glass. However, the tablet needs to be mounted to a fixture on the workstation so that users can have both hands free for the assembly work. The relatively fixed position limits the flexibility to adjust for individual users' conditions and can create potential ergonomics problems in the long run. The questionnaire result shows both voice command and touchscreen buttons worked well to control the assembly flow, but confusion of pronunciation and even which langue to use were noticed during the test. These findings highlight the new challenges both XR system users and developer are facing, which a systematic approach of incremental development that constantly getting feedback from the end users can help companies to reach the idea system for the specific manufacturing problem.

In short, the latest AR technology shows great potential to support future assembly tasks, but both users and developers lack the "common sense" in such AR systems as compared with desktop or touchscreen ones. Further research is needed to establish such standards and principles, which would help smooth and speed up the AR integration in manufacturing.

FIGURE 5. The AR interface with visual aid for the order picking in HoloLens.

C. CASE 3

1) BACKGROUND

Order picking is estimated to account 55% of the total cost in the warehouse [64]. This is especially a challenge for manufacturing companies that are facing the shifting trend from mass production to mass customization [60]. Digital technologies such as handheld tablet with scanner as well pick-by-light systems are examples of the effort that have been reported to improve the order picking speed and quality [65]. With the latest advancement in AR technology and wearable hardware, more research are starting to investigate the potential of integrating AR technology for order picking. It is believed that operators could improve their performance as wearable AR devices can provide intuitive information presented right in front of eyes and free both hands for the order picking tasks [66].

2) RESEARCH PROCESS

An empirical case study that aims at developing and evaluating the effect of AR supported order picking was conducted at a ventilation and indoor climate solution provider based in Sweden [67]. The variety of products and high level of customization requirements in this field makes it a well-suited case for the study. The study carried out interview and onsite observation at first to understand the current practice, then literature review was done to establish measurement criteria as well as selection of AR device. Thereafter, a pick-by-vision AR system was developed using software platform Unity3D and Microsoft HoloLens as the hardware. The developed AR interface is illustrated in Fig. 5. Two orders consist of 12 and 14 items each were implemented with the AR support and it was tested by five representatives from the company. Each participants performed the two order picking tasks twice and the whole process is recorded in video for later analysis in relation to the measurement criteria. After the test, all participants also filled in a scale-rating questionnaire with different statements. The result together with the analysis of the video recording were used to interpret the effect of the AR system.

TABLE 1. The comparison of order pick time between the developed ar system and current system.

	Order A (12 items)	Ordre B (14 items)
AR	348s	364s
Benchmark	252s	354s

3) RESULTS AND CONCLUSION

All participants managed to pick the correct items, but the average picking time is longer than the benchmarked normal level. The details of the time different between the test scenario and the benchmark level is shown in Table 1.

Most participants performed better with shorter time in their second round and order B shows a much smaller difference as participants had more experience with the AR system. After analyzing the video recording, the main problems that are identified are user habit, application limitations and the device limitation. The wearable AR device is new to users and it takes some time for users to get used to the new systems even though a short tutorial of how to use the system was done prior to the test. The developed system also lacks the usability focus and has some obvious design flaws. For example, the white text is difficult to read. It has burden the user and partly resulted in the unsatisfactory performance. The narrow field of view (FOV) and inside-out tracking from the chosen device also affected the usability as the augmented visual indicator that are supposed to guide the users can end outside of user's perspective and put an extra requirement to users to learn from experience. The less desirable result from the study indicates hardware and software selection would ultimately affect the final outcome of the intended XR system. It is therefore important to set a rigours process to evaluate the capabilities of potential solutions against the identified requirements for the specific manufacturing related task.

Despite the shortcomings described above, the study still shows great potential of improve order picking using wearable AR systems. The scale rating result also agrees with the potential but more research need to be done to improve the usability of such systems.

D. CASE 4

1) BACKGROUND

Given the close to life experience and ability to play what-if scenario in relative ease with VR systems, it has attracted increasing interests to adapt it for improving assembly training [68]. However, interaction design for VR systems in 3D is different from the previous 2D dominated systems. Design principles worked well for 2D systems are not guaranteed success in VR [34]. Reality-based interaction (RBI) was proposed as a framework to support the VR system design [69]. The core principle is to create interface objects that users are already familiar with. The benefit of such an approach are the reduced mental effort for users to understand and learn in VR systems [70]. On the contrary, the concept of reality trade-offs emphasizes the importance and necessity

TABLE 2. The implementation details of reality-based interaction and reality trade-offs inspired approaches.

	Scenario RBI	*Scenario RTI*
Virtual environment	• Point cloud representation of the actual drone factory • Same layout of the actual workstation • High level of relistic visualization environment	• Only a minimalistic workstation with the necessary components.
Instructions	• Text and picture instruction in a virtual display	• Visual aid through colored active zones
Process	• Components are picked from different plates as in real case • Only correct placement of component will proceed to next step	• Components pop up automatically in a fixed postion within the view. • Only correct placement of component will proceed to next step

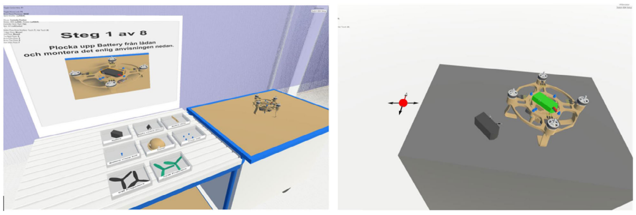


FIGURE 6. Reality-based interaction design (left), reality trade-offs inspired interaction design (right).

of beyond reality interaction in VR, such as grab objects from distance and teleport to navigate for improved user experience [71]. The boundary between these two approaches is not clear and needs further studies to better support future development of VR assembly training systems.

2) RESEARCH PROCESS

To better understand the effects of assembly training in VR that follows RBI and reality trade-offs inspired (RTI) approaches, an empirical case study was conducted [72]. The case chosen is the drone factory in a Swedish national testbed laboratory, where 3D printed drone parts are assembled in different workstations. A VR assembly training system was developed. It covers the assembly task in one workstation that has 14 steps. Both RBI and RTI approaches were implemented with the same task as shown in Fig. 6, which gives two unique scenarios to study the effect of training outcomes. The details of the two scenarios are listed in Table 2. There are in total 22 participants took part in the study. They were randomly assigned to the two scenarios, thus resulted with 11 users for each scenario. Each participant went through the same procedure from introduction tutorial, assembly training in VR, assembly of real product and follow-up questionnaire. The completion time and numbers of errors were recorded for all participants during both the VR training session and the real product session. The data was analyzed together with the questionnaire result to answer the potential effects of the two interaction design approaches.

3) RESULTS AND CONCLUSION

While the completion time of RBI scenario is on average 42% longer than the RTI scenario in the VR training part, the real world assembly show no big difference for the two scenarios. The number of errors made during the assembly does not show any significant difference either. When it comes to the closeness of VR training with the actual assembly task, RBI scenario received a slightly higher average rating of 4.64 while RTI with 4.45. Both values are high in a 1–5 scale where one and five indicate completely different and completely the same respectively. Another interesting finding is that prior experience with assembly work shown no obvious effect on the training outcome, but prior experience with VR systems has a noticeable correlation with better performance.

The results shows the RTI approach is preferable for this specific assembly-training task due to the less effort in development and almost the same training outcome. However, it is difficult to generalize from this study, as the chosen assembly task can be too easy to learn and thus reach the so-called ceiling effect. Additionally, the chosen task has no safety related concerns that a more realistic VR system with RBI approach would provide more value. However, it is clear that further studies on interaction design for such VR systems used for assembly training are needed, so that suitable approach with regard to optimal outcome can be chosen by individual cases. The implication of the study also pinpointed to the interaction design challenges associated with the XR system for both users and developers. Thus, a systematic approach with iteractive development should be adopted for future development.

E. CASE 5

1) BACKGROUND

In the competitive area of truck manufacturing, companies are changing the business model from pure product sales to ''product-as-a-service'' [73]. In this transition, the product maintainability becomes pivotal to the success of the new business model. The conventional product development cycle

TABLE 3. Scale-rating result comparing VR experience with desktop solution and physical product.

	The VR system	Desktop solutions	Physical product
Realism of situation (surrounding awareness)	4	2.8	5
Understanding of product properties (size, function in context etc.)	3.9	2.6	4.7
Ability understand the variants effects on information creation	3.8	2.9	3.8
Perform ergonomic analyses	3.3	2.3	4.9
Perform requirement analysis	3.7	2.6	4.9
The trust of the findings in the performed analysis	3.6	2.9	4.7
Communicate information between roles and departments	4.1	3.3	4.2
Test and verify solutions	3.2	2.3	4.8
Ability to identify errors	3.8	2.9	4.7

is serial and makes maintenance evaluation usually come in late in the process, which would increase cost and make it hard to adapt product design for better maintainability [74]. Moving maintainability analysis to the early phase of product design is believed to detect potential errors early and would therefore help developing reliable products that are easy to maintain [75]. To facilitate the transition, various digital technologies such as computer-aided design (CAD) has already been widely used in product development [76]. In recent years, the extended reality (XR) technologies becomes ever matured and promise even better support with the flexibility to play "what-if" scenario and intuitive visualization of design concepts [77]. Therefore, this study is set out to investigate the feasibility and potential benefit of integrating XR technology for maintainability analysis early in the truck development process.

2) RESEARCH PROCESS

An empirical case study was conducted at a truck manufacturer in Sweden [78]. The study started with understanding the requirements through interview, contextual inquiry and affinity diagram during a workshop. At the same time, a literature studies about different XR systems was done so that suitable XR technologies can be decided. In this case, a VR system with nature hand tracking feature was chosen and therefore developed based on the requirements, which provides four scenarios of maintainability analysis in VR. One of the scenario where service engineer can design the service method is illustrated in Fig. 7. The developed VR system were tested by nine representatives from the case company. After each participant has completed the four tasks in VR, feedback was collected through semi-structured interview as well as a scale-rating questionnaire comparing the VR experience in relation to perform the same tasks with conventional desktop solution and physical product.

3) RESULTS AND CONCLUSION

All participants believed that through the VR system, it could better communicate the product concepts across different function groups, so that potential problems of product maintenance can be detect early in the development process. The nature hand tracking made accessibility evaluation as ease

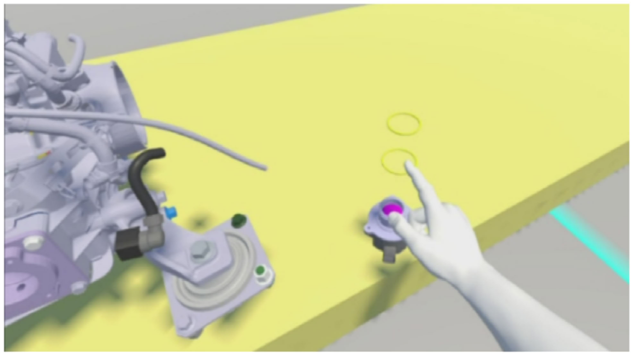


FIGURE 7. Service engineer is designing the service method in VR.

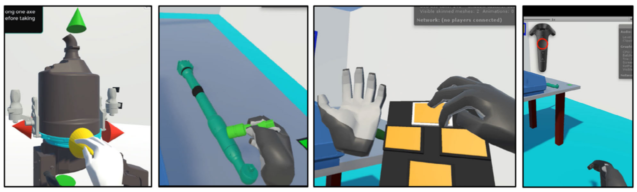
as with real physical product. However, geometrical analysis in this VR system is difficult. It would be more efficiently just using the conventional desktop computer system. The questionnaire results shown in Table 3 confirm with what are extracted in the interview. The scale is from one to five with one represents very poor support and five means very good support.

The data compatibility problems that were reported in other XR system development was most evident in this study. By directly converting the CAD data created by product designer to the format supported in VR systems, it is not only time-comsumping but also affecting the user experience in VR. Because it brings in the internal structure data that are not relevant for the VR review work, but greatly reduced the rendering quality of the VR visualization. This is especially a big challenge for XR systems that involves heavy interchange of data between different systems. A streamlined data pipeline need to be established for such cases.

To conclude, a VR system with hand tracking feature is developed to support the maintainability analysis early in the product development phase. It has shown advantage in communicating product concepts to different stakeholders and potential to detect design errors early. Therefore, contributing to the successful transition to the product-as-a-service model for truck manufactures.

TABLE 4. Effects on user experience for bare hand interaction and controller based interaction.

		Bare hand interaction	*Controller based interaction*
Immersion		+	/
	Large objects	-	+
Interaction	Small objects	/	+
	Menu buttons	/	+
Autonomy	Navigation/teleportation	-	+
		Activity: spotwelding training	
		Activity: Product design review for service tool accessibility	



a b c d

FIGURE 8. Hand pick large object (a), hand pick small object (b), navigation palm menu (c), controller interaction (d).

F. CASE 6

1) BACKGROUND

Virtual manufacturing is recognized as the emerging approach for manufacturing companies to improve their processes to cope with the increasing global competition [79]. With the latest advancement of VR technologies, many studies reported the advantages of VR that would push the virtual manufacturing approach one step further [2]. The user experience of such VR systems in terms of immersion, interaction and autonomy are believed to be crucial to the successful integration of VR in manufacturing [80]. Bare hand interaction (BHI) that enables users to interact with digital content using hand gestures are reported with improved user experience in VR systems [81], [82]. In pursuit of clear knowledge on the interaction design of VR systems used in manufacturing context, it is worth finding out what different effects on user experience with the BHI and normal controller-based interaction (CBI) approaches.

2) RESEARCH PROCESS

This study was conducted at the research and development center of an international automotive company situated in Sweden. Two virtual manufacturing activities were chosen. The first one focused on training spot-welding operators and the other supports product design review for service tool accessibility. A VR system that support both activities were implemented with the two interaction approaches: BHI and CBI, as shown in Fig. 8. The system was thus tested and evaluated by 22 engineers in the case company. The data were collected with regard to the immersion, interaction and autonomy and therefore comparison of the different effect on user experience was made for these two approaches.

3) RESULTS AND CONCLUSION

The data gathered from all participants performed both activities were analyzed with regard to the three user experience aspects: immersion, interaction and autonomy and therefore illustrates in Table 4. The inclusion of hand tracking and synchronized visualization of hand models are highly preferred by the users as it gives them a more realistic feeling during the VR sessions thus can bring positive effect to the level of immersion. However, the different details and quality of hand models that are being rendered seems has no significant impact to user's perception. Hand interaction with virtual objects such as basic pick and place actions were found to be overall more complicate than using controllers. It has shown extra difficulty when using hand tracking to move large objects as the tracking sensor used in this study is mounted on the HMD, which is not as stable as the stationary sensors. The palm associated virtual buttons for navigation is proved to be cumbersome for all users as both head where sensor is positioned and hand where direction of moving is pointed need to be stable so that movement can be smooth.

It is worth noting that the drawback reported from this study can be the result of a low-end hands tracking sensor. Other advanced hand tracking system that use stationary sensor or on-hands attached sensors may provide a better result. However, it is still clear that the biggest benefit of bare hand interaction is the increased immersion. It can be an optimal approach for future VR systems in manufacturing context to adopt a mixed approach, hand tracking and controllers are for enhanced immersion and interaction respectively.

The implication of this study also highlight the fact that while various XR hardware and software are bringing in new solutions and potential improvement for existing work practices, the new mediums to present information and interact with the system can also be the obstables for the wide adoption in industry. It is therefore pivotal to involve users early and throughout the development process to achieve the successful XR adoptation with higher user acceptance.

G. CONSOLIDATION OF THE CASES

A cross-analyzed of the six cases against the defined SDLC phases was conducted to extract the critical factors and challenges in each of the development phases.

1) IDENTIFYING PROBLEMS

This is the first and important phase for the system development, specific manufacturing problems need to be identified. All of the six cases started with clear problems that needs to be improved. It requires knowledge and experience in the related manufacturing fields to accurately define the scope of the problem. Interviews and contextual inquiry that carried out at the actual manufacturing sites have proved to be effective in identifying the potential problems as multiple interviews and field observation with the responsible engineers were carried out in all of the presented cases. Additionally, methods such as affinity diagram and storyboard used in case 5 and 6 helped better communicate back to the manufacturing engineers about correct understanding of the intended problems.

2) ANALYZING THE NEEDS

After the problem has been identified, the next phase focuses on specifying the requirements of the system. It involves the matching between the technological solution and the specific problem. The positive results achieved in case 2 and case 4–6 reflected the suitability of the chosen XR solutions, while the less satisfactory results in case 1 and case 2 were largely associated with the chosen hardware. In case 1, the solution with the cabled AR glass connected to a laptop requires extra preparation and setup time when performing the maintenance task, which makes it less practical in the real factory environment. Case 3 concerns about order picking support in large warehouse using AR instruction. The hardware limitation of position tracking in spacious environment reduced the reliability of the system and thus delivered a less favorite experience.

3) DESIGNING THE SYSTEM

In this phase, information collected in the earlier phases are used to accomplish the logical design of the system, whereas accurate data entry procedure is defined. All the cases experienced certain degree of difficulty in this phase due to the fact that various data formats used in existing systems. Data conversion became an inevitable step in all the cases. It is time consumping and potentially affecting the quality of data. In case 4–6, contextual data of the actual manufacturing environment had to be created using 3D laser scanning technology. The cases have shown the importance of a clear data pipleline would affect the overall quality of the XR systems.

4) DEVELOPING AND DOCUMENTING

This phase concerns about the actual work of implementing the XR system. All the cases used the open platform Unity3D for the integration and programming. The large and active developer community as well as the support for different XR hardware ensured the smooth development. Moreover, the module development with incremental features enabled the developed systems to be adapted with dynamic changes.

5) TESTING THE SYSTEM

The developed system then needs to be tested by the users. It can take place when the whole system was completed or when parts of the features have been developed. All the six cases have undergone at least one formal user test to evaluate the usability of the system as well as getting the feedback for future improvement. It is desirable to perform such tests multiple times to ensure the outcome of the developed system. However, it is also a balance between the project complexity and available resources. For example, case 1 conducted two user tests due to the limited knowledge about AR usage for the specific manufacturing problem at the time and the poor result from augmented text instruction directed the AR system to visualize instruction in the more favorite 3D animations in the late development.

6) IMPLEMENTING AND MAINTENANCE

In the conventional SDLC, this phase concerns about the transition to the new system and the future update for potential improvement. Due to the limited scope in the presented cases, it is not relevant about the actual transition. Instead, the execution of the six cases suggested continuous improvement with the iteration within the phases can make the development better adapted to the new and rapid changing XR technologies. While linear execution of the phases and iterate though complete cycle would improve the system, the approach that allows revisit to earlier phases before the completion of full development cycle is believed to bring more flexibily and better suited for the XR systems development in the manufacturing context.

V. THE PROPOSED FRAMEWORK

Given the summary and consolidation of the cases against the SDLC in the previous section, a five-step framework of user-centered extended reality system development was synthesized and illustrated in Fig. 9. It suggests a systematic process with iterations of five serial steps for XR system integration in manufacturing context, which are based on the success experience and lessons learned of the empirical cases.

A. STEP ONE: UNDERSTANDING REQUIREMENTS

It may sound obvious that clear and accurate requirements are the necessary very first piece of information one should have for any system development. However, it is not uncommon that this step is often skipped or downplayed in practice, which would result in unsatisfactory outcome. More importantly, the manufacturing context is much more complex than ordinary use case scenarios. For example, in the case study one and three presented previously. The outcome of the developed AR systems were largely affected by the relatively careless requirements inquiry. In case three, the order-picking operation is carried out in a narrow but long warehouse, where inside-out tracking from the chosen device has the worst tracking performance. Thus, the positioning of augmented visual aid was not always precise and negatively affected operator performance. In case one, it was not clear at the beginning whether the AR system would be used to train maintenance-operators offsite or support the actual maintenance activities onsite. This would result with completely different choice over the different AR devices.

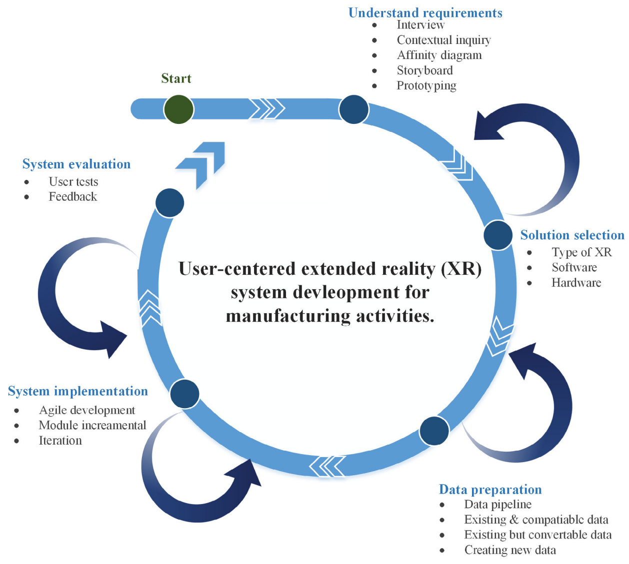


FIGURE 9. The framework of user-centered extended reality system development for manufacturing activities.

Therefore, to obtain a thorough understanding of the requirements is an important first step towards a successful development of XR system for manufacturing. Methods such as observation, stakeholder workshop, contextual inquiry, storyboard and prototyping adopted from the user-centered design [83] approach are proven effective in identifying the requirements. Observation and contextual inquiry focus on understanding the essential characters of the intended tasks. It should answer the following questions:

- What actions are taken? (Step by step operation list)
- What support are used? (Instruction and tools involved)
- What outcome are achieved? (Operation result)
- What main drawbacks are there? (Points for improvements)

With the above questions answered, storyboard of the new work routines with XR system support can be developed and further detailed with prototyping of the specific user interfaces. Therefore, not only developer and product owner, but also the end user could join in to evaluate and give feedback on potential misunderstandings until the final requirements are settled. In this way, well-communicated and approved requirements would pave the road for the following steps.

B. STEP TWO: SOLUTION SELECTION

Given the various types of XR technologies and the associated choices of different hardware and software available today, determining the suitable solution is a difficult and important decision. The choice was often made on what hardware or software are already available at the company rather than which solution best fulfill the identified requirements. On the contrary, the detailed description of XR technologies as presented in Section 2 should be examined carefully against the obtained requirements, so that a suitable solution in terms of XR system type, hardware and software can be determined.

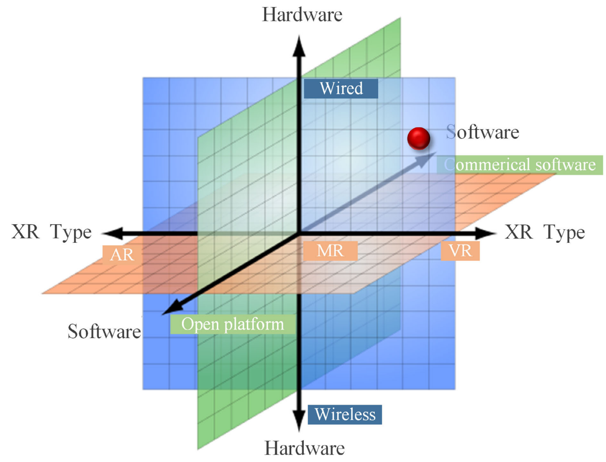


FIGURE 10. The three-axis that define an XR system.

The three aspects that define an XR system are illustrated with a three-axis graph shown in Fig. 10.

The X-axis is about the XR technology type that follows the reality–virtuality continuum with AR and VR on each end and MR in the middle. Depending on the different phases of manufacturing the intended XR system would be used, the right XR system can be determined based on the different manufacturing phases [17].

The Y-axis concerns about the hardware to be used. It can be relative simple choice between wired and wireless devices, but also include technical specification of different devices, such as the FOV, resolution and frame rate of the HMDs. Depending on the specific requirements, decision on additional devices that provide features like BHI or haptic feedback should be made.

The Z-axis focus on the software part of the XR system. Choice should be made between established commercial engineering software and open platform development. As described in Section 2, most of the established commercial software that manufacturing companies are already using today, have started to support XR features. If the existing commercial software can meet the identified requirement, it can be a better choice than developing everything internally. However, for company that needs highly customized features or security concerns, it may be worth spending the time and effort to develop its own using open development platform. It is a tough decision that should consider cost, return of investment (ROI) and expertise available at the company against the identified requirements.

One example that followed this process of selecting the appropriate XR system is the use of VR for factory layout planning [84], where various stakeholders should be involved in the virtual session to design and evaluate new factory layouts. The final solution fell into the red cycle shown in Fig. 10, where wired VR headsets were used and supported with customized functions developed in open platform Unity3D.

C. STEP THREE: DATA PREPARATION

XR system needs to be populated with various data so that a rich virtual experience can be provided for the intended activities. The data ranges from basic geometry files to the associated meta information such as attributes and instructions, as well as contextual data of the factory environment. Since most of these data were created before the introduction of XR systems, the data compatibility is a big challenge for XR development. There are certain data used in daily manufacturing, which have not been digitalized as well. For example, it is very rare for manufacturing companies to have the update virtual model of their factory plants. It is also no surprise to find companies without digitalized work instruction.

Therefore, preparing the needed data for the XR system is not an easy task. Depending on the specific requirements of the XR system and the company's choice of solutions. Companies need to develop a suitable data pipeline based on their own circumstances. It means that there should be a digitalization strategy that takes into account of XR compatibility. For example, CAD models of the products can be directly or with easy modification to be XR ready. This would prevent the loss of information during undesired data conversions and it will reduce the amount of extra work spend in re-modelling for XR.

A suitable data pipeline will vary greatly for each company depending on the existing modelling software and the chosen XR solution. The best scenario would be that digital data are compatible across the different systems used in the company. It is relatively easy to achieve such a compatibility when established commercial engineering software with XR features can meet the requirements, and then systems from the same family tree often work well with each other. However, when open platform development was chosen for the greater flexibility to test customized XR features, it is crucial to develop an effective and efficient data pipeline connecting existing digital data with the XR system. Another important note is that data pipeline is not only one way from existing data to XR, but also the other way around. It should be both ways so that the changes made in XR can export back to the upper stream of the process.

D. STEP FOUR: SYSTEM IMPLEMENTATION

This step varies for the commercial software and open platform approaches. With the commercial software approach, it means that an existing software, which fulfilled the requirements, is ready for use. So there is no system development involved, but rather learn to use the software. With the open platform approach, the system needs to be developed first. In different companies, the system development work can be done internal with a dedicated development team or outsourced to professional software companies. As long as the previous three steps have been completed properly, this process will be straightforward to implement. This study will not go into detail about software development, but would suggest agile development method [85] for the XR system development as the core principle of breaking down requirements into large iterations of small incremental functioning modules greatly influenced all the development of the six presented cases.

E. STEP FIVE: SYSTEM EVALUATION

A system evaluation plan needs to be drawn based on the development plan and available resources at the company. At least one formal user test that involves different stakeholders should be conducted for any version release of the XR system. Through the tests, user feedback and performance can be collected and analyzed for further improvements.

All the XR systems developed in the presented cases have been tested at least once by the stakeholders. Some of the systems were tested multiple times along the development. It has proved to be an effective way to detect potential usability related issues and ensure the quality of the outcome.

A formal user test needs to be carefully designed and conducted. There are many established methodologies for desktop computer system evaluation [86], [87]. They can be adapted to the XR system used in the manufacturing context, while keeping the same fundamental rules emphasized in the next paragraph.

The entire test procedure should be designed and finalized in details prior to the test. For example, it should clarify the test objectives and the associated measurements needed to answer the questions. It is also important to have standardized manuscripts for moderator to guide each participant through the test so that consistent test can be achieved. Both objective and subjective data should be collected for better interpretation of the results. Objective data through quantitative measurements are often performance related such as task completion time and rate, while qualitative data of participants' subjective view regarding the intended system can be captured through the widely used system usability scale (SUS) questionnaire [48] and/or follow-up interviews. Finally yet importantly, the recruited participants need to represent all the stakeholders of the XR system.

F. ITERATION

Developing an effective and efficient system is never an easy task; especially in this case that it is about the introduction of the novel XR systems in the already complex manufacturing world. The development process should not stop here but rather iterates with small incremental improvement until the idea system for the specific requirements is in place.

The iteration can happen after all the presented steps have been carried out in sequence, which forms a complete circle of the development. In certain cases, it also needs revisit to previous steps before continuing with the circled framework. For example, with the rapid development in the XR technologies, the release of a new hardware may make the previously deemed impossible requirements now as a possibility, then it is necessary to revisit the requirements definition and make the suitable changes before proceeding to the next step.

VI. FRAMEWORK VALIDATION

The framework was applied to an empirical case to evaluate the applicability. Additionally, it was validated through six identified previous studies that partly aligned with the proposed framework.

A. THE EMPICIAL CASE

The proposed framework was adopted in the development of a VR tool to support product design review in an automotive company. A summary of the execution and outcome is presented below. A more detailed report can be found at [88].

1) REQUIREMENT ANALYSIS

The case concerns a globally distributed automotive company with research and development in Sweden and factory plants in China. The specific task is about design review of new fixtures for spot welding in car body production. Internal documents of related work procedures were studied, a stakeholder workshop was held, and paper prototypes were used to be better understand current practice and envision the desired improvements. Current practice relies on CAD software to communicate design concept across different teams that situated in distributed locations. It also requires one or more physical prototypes for verification before final installation. The main drawbacks are the lengthy process in the communication and cost associated with physical prototypes. Additionally, end users, which are the operators of fixtures lack the expertise in CAD design which prevent them from influencing the design.

Therefore, detailed requirements were set and some of the key points are listed below:

- A virtual tool for all stakeholders that is intuitive to visualize and interact with the new product designs
- Multiple stakeholders can join in the same virtual session from different locations.
- All stakeholders can communicate verbal
- Virtual sessions can be recorded in image or video for documentation and potential communications.
- Personalized virtual representations of each stakeholder for identity and engagement.
- Role associated functionalities for moderator, participant and spectator.

2) SOLUTION SELECTION

With the obtained requirement list, it is examined against the state-of-the-art XR technologies to decide on the preferred solution. VR was chosen over the others for its completely immersive environment, which is believed to provide more intuitive visualization and interaction for all stakeholders. Immersive HMD and desktop VR setup were both supported so that different user roles can choose the suitable setup. Open platform, Unity3D was chosen for the software implementation because of its active community and available resources that reduce the complexity of developing the customized functionalities.

3) DATA PREPARATION

There are mainly three different types of data to be used in the VR system. Firstly, it is the geometry data of the products. The case company use CATIA[6] in design that is in.jt-format, which is not supported, in the chosen VR solution. Therefore, a data pipeline to convert it to VR-ready formats was realized using a plugin PIXYZ.[7] Secondly, it the personalized avatars. The AvatarSDK[8] was chosen as it can generate realistic 3D model of human head based on one front-faced user photo. The last type is the contextual environment data, which increases the realism of the VR environment. It is through 3D laser scanning of the factory plant and post-processing of the obtained point cloud representation to be rendered in real-time in the VR system.

4) SYSTEM IMPLMENTATION

The VR system was developed with module functions following the agile development principles. It adopted existing open source software development kits (SDKs) to avoid reinventing the wheels and speed up the process. SteamVR[9] and Virtual Reality Toolkit (VRTK)[10] were used to form the foundation various interaction. Photon Unity Networking 2 (PUN2)[11] served as the backbone for multi-user features.

5) SYSTEM EVALUATION

User tests were conducted on two occasions to evaluate the system. The first user test was carried out at the end of the first iteration with parts of the features implemented. The main objectives of the test were to verify the quality and reliability of the multi-user connections as well as getting feedback on the review related interaction design. A second user test took place when the second iteration of development improved the system with the feedback acquired in the first round. There were 14 stakeholders from the case company join the test, the usability with regard to whether the VR system can be used complement or even replace current practice was evaluated. The user acceptance towards such systems were also collected through questionnaire and follow-up interviews.

6) OUTCOME

A functioning multi-user VR system was developed for product design review. It supports maximum 20 users to join in the same session from any locations with internet connection. The system is reliable to synchronize virtual objects and audio for discussion in the virtual review. Distinct user identify was achieved through personalized avatars and different user role definitions. It is also flexible with the needed hardware to access the system as no HMD is needed but a normal computer is enough if the user is to moderate or speculate the review session.

The test results show that virtual review session can be held in ease with stakeholders from different background. Especially, it enables operators of the product to be involved and

[6] https://www.3ds.com/products-services/catia/
[7] https://www.pixyz-software.com/
[8] https://avatarsdk.com/
[9] https://store.steampowered.com/steamvr
[10] https://vrtoolkit.readme.io/
[11] https://doc-api.photonengine.com/en/pun/v2/

TABLE 5. Summary of the validation studies against the proposed framework.

	Area	Requirement	Solution	Data	Implementation	Evaluation
Study A	VR Harness Assembly	X	x		X	x
Study B	VR Assembly	X			x	X
Study C	MR Design review	X		X	X	X
Study D	AR Assembly	X				X
Study E	VR Safety training	X	x		x	X
Study F	AR Assembly	X		x	X	x
Study G	MR Quality control	X			X	X

contribute in the design phase. The scale rating results suggest that all the participants agree that this tool is beneficial for product design review and are willing to use such a tool in their future work, though further development of review work related functionalities are desirable.

In short, the development was successful to deliver a VR tool that supports product design review with basic functions and it has received a high user acceptance.

B. EXTERNAL VALIDATION

To further validate the proposed framework, a literature review of XR system development papers was conducted. Seven studies with successful integration of XR systems in manufacturing have been identified. All of them took similar approaches that partly aligned with the proposed framework without explicitly outline it. The studies are shorten as Study A [89], Study B [90], Study C [91], Study D [92], Study E [93], Study F [94] and Study G [95], which are summarized against the framework procedures in Table 5. Uppercase X represent extensive coverage, while lowercase x means brief cover.

The commonality of these studies is that the user-centered design approach was to large extend applied throughout the development. Therefore, the requirement analysis and system evaluation phases were well aligned with the proposed framework. Even though Study A and Study F had a narrowed focus only in the usability associated with performance and lacked the user acceptance evaluation. All studies except Study D have adopted the module development. These procedures have ensured the developed XR systems met the requirements with acceptable usability as well as overall positive attitude towards the technology. The biggest deviations are the solution selection and data preparation phases. From the reports, it is not clear how the hardware and software were chosen against the requirements, but rather use what already exist. This may result in less appropriate solution was chosen which would affect the outcome.

To sum up, these studies further validated the proposed framework would help XR system development in manufacturing context to achieve a higher usability and user acceptance.

VII. DISCUSSION

The frameworks presented in this thesis provides guidance to manufacturing companies in their XR integrations. They were developed based on the results of the different empirical cases, which address identified critical factors and mitigate potential negative impact, so that the promised benefits of XR technologies may be reaped in practice. Due to the multi-disciplinary nature of the problem, the frameworks cover the extent of the necessary steps but lack in-depth guidance for each step. They therefore serve more as general guidance providing an overall picture of the XR system development for manufacturing. Accordingly, they should be applied in combination with other established methods during the actual implementation of each step. For example, in the understanding requirements step, methods and techniques such as contextual inquiry (from the user-centered design approach [96]) might be adopted. The evaluation method for AR glasses developed by Syberfeldt *et al.* [22] may be a good aid to finding a decent match during the solution selection step. In the system implementation step, methodologies from the software engineering such as agile development [85] may be adopted to ensure efficient development.

Our pragmatic worldview has led to the use of multiple case studies. It also helped the authors not to view the manufacturing systems an absolute reality. It enables the authors to use different research methods in this study. The multiple cases used in this thesis offer the advantage of directing the research to fulfill the research aim by collecting both qualitative and quantitative data. Research design relying solely on a qualitative or quantitative approach would have conflicted with the authors' pragmatic worldview and led towards either a subjective or an objective view. Therefore, the research approach taken in this thesis included design, data collection, implementation and data analysis [47]. Any changes in this process could have altered the outcome of the thesis. However, to keep the balance between the usefulness and rigor of the research, validity and reliability were also taken into consideration when designing and conducting it. The methods used were validated according to construct and internal, external and contextual validity [97]. For example, multiple cases with different companies and participants were used in the empirical studies, which increased the external validity. Both qualitative and quantitative data was collected to validate the results, so that internal validity was ensured. The data was captured and stored in a structured way, which increased the reliability of the empirical data [97], [98].

The paper also provides directions for future research. First, further studies are needed, into ensuring a satisfactory user experience (UX) for the XR systems in manufacturing. The progress of XR technology integration into manufacturing would depend heavily on the general UX and user acceptance of the technology. As reported in the previous studies while technological issues about XR system are of importance to the success of integration, the organizational issues are more relevant for industry [45], [46]. The higher user acceptance would help clear out such organizational barriers. The XR development can learn from the conventional user-centered design approach shown to work so well for software engineering. However, efforts are also needed to establish common standards and practices unique to the XR field. Another direction concerns the verification and validation of XR solutions in manufacturing. The potential benefits were largely evaluated using subjective data. It may be difficult to follow up and quantify the actual benefits if an XR system were to be introduced into manufacturing.

VIII. CONCLUSION

This study aims at outline a general guideline for XR system development in the manufacturing context with better usability and user acceptance, so that it can foster wider adoption of XR technologies to improve various manufacturing activities. Six cases concerning about the development of different XR systems for different application areas in manufacturing were conducted following a user-centered design approach. The first contribution is the framework derived from the results of the cases, which consists of five iterative phases: (1) requirements analysis, (2) solution selection, (3) data preparation, (4) system implementation and (5) system evaluation. It is validated through one empirical case and seven identified previous studies that partly aligned with the proposed framework. The study also contribute to the kowledge for industrial practioners so that Manufacturing companies which plan to adopt XR technologies as part of their Industry 4.0 vision may benefit from the clear guideline on the steps needed to integrate XR in manufacturing and it extends the XR usage with increased usability and user acceptance. Such knowledge can help kick-start the integration of XR whilst avoiding common mistakes. Furthermore, it strengthens the importance of user-centered approach for XR system development in manufacturing.

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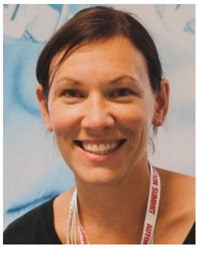

ÅSA FAST-BERGLUND was born in Gothenburg, Sweden, in 1978. She received the master's degree in IT-systems and logistics from the IT-University in Gothenburg, in 2005, and the Ph.D. degree in automation in production systems from the Chalmers University of Technology, in 2012. She worked as a Production Engineer from 2005 to 2007. She is currently working as an Operational Manager for a research lab (SIILab) and as a Professor of smart automation in production systems with the Chalmers University of Technology. She has published over 100 scientific conference and journal articles. She has worked with both cognitive and physical automation; the current area of research is within collaborative robot applications in production systems. She is also a Vice Chair of the IFAC TC5.3, and a member of IFIP WG5.7 and ISO TC299/WG 3. She has published papers at the IEEE conferences on intelligent systems, in 2018, were she also co-chaired sessions and for the ICE conference, in 2020.

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He performs research on the area of how digitalization can aid manufacturing industries to achieve a more sustainable society at large. Areas of interest are circular economy and sustainable development, and in this context how digital tool such as 5G, 3D scanning, discrete event simulation, artificial intelligence, and virtual and augmented reality can be applied for manufacturing industries. He joined the Department of Product and Production Development, Chalmers University of Technology, in 2006 as an Assistant Professor, in 2011 as an Associate Professor, and in 2015 as a Professor of sustainable production. He worked as a Guest Researcher with the National Institute of Standards and Technology, from 2007 to 2010 and from 2015 to 2016. He is currently working as the Vice Head of the Division of Production Systems, Department of Industrial and Materials Science, Chalmers University of Technology. He is also the Director of PMC Europe AB and the Director of the board at the Society of Modeling and Simulation International. He is also an Active Member of AAAS, ACM, and SCS. He received the Swedish Royal Academy of Science Award in Technology 2004, C-SELT 2004, the Alde Nilsson ABB Award in 2003, the Ernst Gerber Jubilee Fund in 2003, and the Chalmers Foundation Scholarship in 2002. He was a General Chair for the Winter Simulation Conference sponsored by IEEE, Gothenburg, in 2018, as well as the Co-Editor in 2009 and the Lead Editor in 2010.